Mon. Not. R. Astron. Soc. **261**, 599–604 (1993)

Infrared and optical observations of the newly identified Be/X-ray binary LSI + 61° 235

M. J. Coe,[1] C. Everall,[1] A. J. Norton,[1] P. Roche,[1] S. J. Unger,[1] J. Fabregat,[2] V. Reglero[2] and J. M. Grunsfeld[3]

[1] *Physics Department, The University, Southampton SO9 5NH*
[2] *Departmento de Matemática Aplicada y Astronomía, Universidad de Valencia, 46100 Burjassot, Valencia, Spain*
[3] *Caltech, Pasadena, CA 91125, USA*

Accepted 1992 September 23. Received 1992 September 18; in original form 1992 July 20

ABSTRACT

Observational infrared (IR) and optical data are presented of the newly discovered Be/X-ray binary system LSI + 61° 235, taken over the period 1991 August–1992 May. Though the IR shows little evidence for any changes, the optical Hα spectrum has undergone substantial modification. Combination of optical photometric measurements with the IR photometry allows the overall spectrum to be investigated and the existence of the Be star's circumstellar disc to be directly confirmed.

Key words: binaries: close – circumstellar matter – stars: emission-line, Be – stars: individual: LSI + 61° 235 – infrared: stars – X-rays: stars.

1 INTRODUCTION

Be stars are a class of emission-line objects that exhibit or have exhibited variable emission features, typically of hydrogen, superimposed on a B-type spectrum. They are usually associated with rapid rotation and are found on or near the main sequence (see Slettebak 1979 for a full definition). It is the presence of these highly variable emission features in a class where they are not expected that makes Be stars unusual.

Within this class of Be stars are the X-ray sources that are known as Be X-ray binaries. For these sources the observed X-ray emission cannot be explained by coronal emission alone, and so a scenario in which a Be star accompanied by a compact companion, usually a neutron star in a wide eccentric orbit, is used to explain the observed X-ray emission. Accretion on to the neutron star, especially at periastron, produces the X-ray activity. About 30 such sources are known (Nagase 1989) and they typically exhibit both X-ray pulsations with periods less than 1000 s (attributed to the rotation of the neutron star) and transient outbursts (Taam, Fryxell & Brown 1988).

The accepted model of a Be star is that of a rapidly rotating star with a flattened equatorial circumstellar disc (Slettebak 1988). The process by which this disc is formed is still not known, but it is thought that variations in the structure and density result in many of the observed spectral variations, although observations in the ultraviolet (UV) have indicated that a more complex model will be required to explain all the features of the Be phenomena (Snow & Stalio 1987). The passage of the neutron star through the disc results in enhanced accretion on to the neutron star and X-ray activity.

In order to help us explore the relationship between the X-ray and the optical/infrared emission, we have established a long-term programme to monitor a group of 10–12 of these targets in both the infrared (IR) and the optical (Coe et al. 1993). Waters (1986) and others have shown that detailed information may be derived concerning the structure of the circumstellar disc, provided that good optical and IR data are available.

The new source LSI + 61° 235/RX J0146.9 + 6121 was recently identified by Motch et al. (1991) from the *ROSAT* sky survey as a potential Be/X-ray system. A low-resolution optical spectrum in their paper identified the presence of Hα emission – presumably from the circumstellar envelope or disc. We have since obtained detailed high-resolution optical spectra confirming this result, and have carried out IR photometric measurements on seven nights spread over three observing runs.

2 OBSERVATIONS

2.1 Infrared data

The IR data were collected in the *J*, *H* and *K* bands using the continuously variable filter (CVF) system and photometer on the 1.5-m Telescopio Carlos Sánchez (TCS) telescope, Tenerife. The data were flux-calibrated by comparison with standard stars and the repeatability of the measurements from night to night is clear from the results presented in Table 1. From this table it is possible to see that there has been little evidence of any significant variation in the IR flux over this 6-month period. Assuming no change in IR flux levels, it is possible to average these data to obtain the mean value of $(J-K)=0.37\pm0.02$.

2.2 Optical spectroscopy

Optical spectra were collected with two telescopes on two different occasions. The first was on 1992 August 28 with the 2.5-m Isaac Newton Telescope on La Palma using the Intermediate Dispersion Spectrograph with the GEC6 CCD detector, providing 0.36 Å channel^{-1} resolution over the spectral range 6480–6680 Å and an exposure of 1000 s. This spectrum was taken within a few hours of the fifth IR data set, and hence the combined data effectively represent a 'snap-shot' IR-optical view of this source. This spectrum is shown in Fig. 1. From this figure it may be seen that the Hα profile is more than a simple single peak, since it exhibits a red shoulder which is just resolved from the stronger blue peak. The total equivalent width of the line is -7.7 ± 0.1 Å.

The second set of optical data were collected on 1992 May 19 with the Palomar 1.5-m telescope, using the P-60 echelle spectrograph. This produced spectra with a resolution of 0.18 Å channel^{-1} over the wavelength range 6521–6663 Å. Two consecutive spectra were taken with exposures of 1000 and 500 s, the combined result being shown in Fig. 2. The equivalent width of the overall Hα profile is -7.6 ± 0.1 Å – in good agreement with the 1991 August result. However, it is obvious that, though the flux may not have changed, the shape of the Hα profile certainly has. These data clearly reveal two separate wings to the emission line with a distinct absorption feature in between, centred on the Hα rest wavelength. The separation of these two wings corresponds to a velocity shift of 137 ± 23 km s^{-1} from the rest wavelength of Hα.

Table 1. IR photometry of LSI + 61° 235.

Date	J	J error	H	H error	K	K error
23 Aug 1991	10.04	0.04	9.80	0.03	9.63	0.03
24 Aug 1991	10.02	0.09	9.82	0.05	9.66	0.05
25 Aug 1991	9.96	0.04	9.72	0.03	9.55	0.04
27 Aug 1991	9.92	0.03	9.69	0.03	9.54	0.03
28 Aug 1991	9.94	0.03	9.71	0.02	9.58	0.04
01 Dec 1991	9.95	0.05	9.76	0.06	9.66	0.06
12 Feb 1992	9.92	0.03	9.66	0.02	9.54	0.03

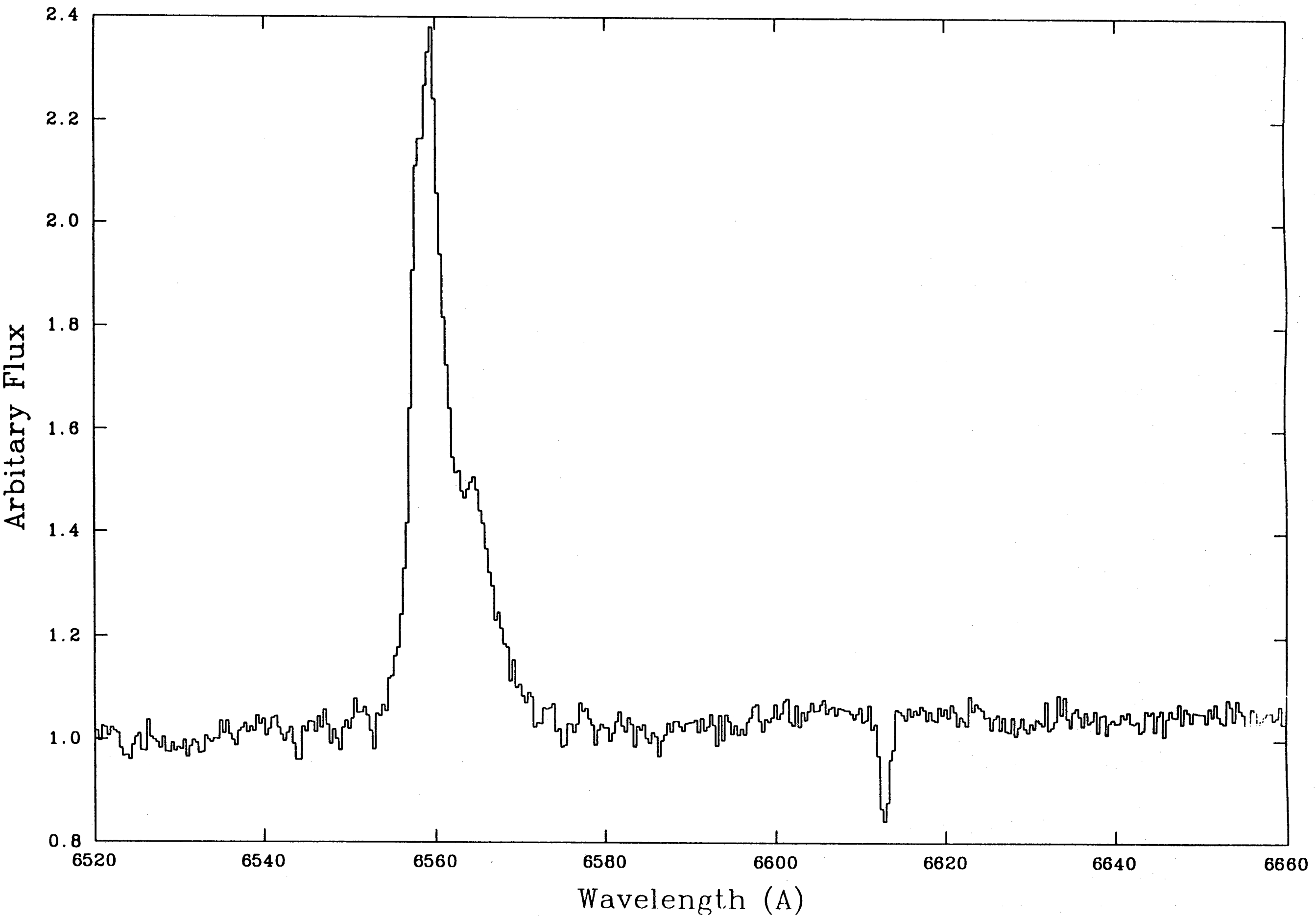

Figure 1. Optical spectrum of LSI + 61° 235 centred on Hα taken on 1991 August 28 with the Isaac Newton Telescope.

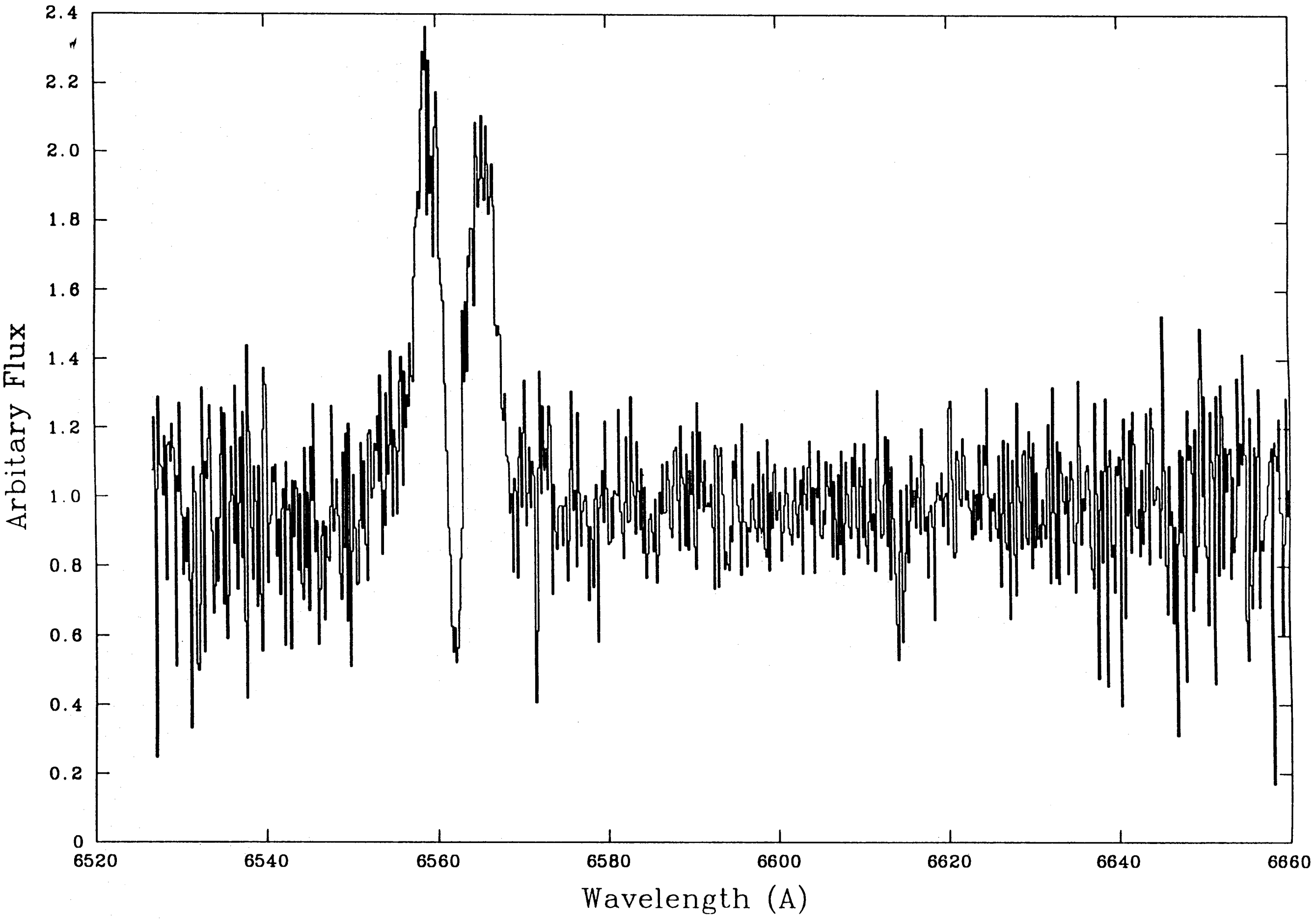

Figure 2. Optical spectrum of LSI + 61° 235 centred on Hα taken on 1992 May 19 with the Palomar 1.5-m telescope.

Table 2. Optical photometric measurements of LSI + 61° 235.

Date	V	b–y	m1	c1	β	B–V	U–B
16 Nov 1991	11.45	0.571	–0.243	0.127		0.62	–0.41
19 Dec 1991	11.52	0.566	–0.259	0.154	2.471	0.60	–0.42
20 Dec 1991	11.51	0.571	–0.247	0.132	2.475	0.62	–0.41

2.3 Optical photometry

Strömgren *uvby* and Crawford Hβ photometry was obtained with the 1.23-m telescope of the Spanish-German Astronomical Center located in Calar Alto (Almería, Spain), using the GEC10 CCD detector equipment with the *uvby* and Hβ narrow and wide filters. The data were collected in two runs, in 1991 November and December. A sufficient number of standard stars were observed in each run in order to compute the atmospheric extinction coefficients and the transformations to the standard systems. A detailed description of the acquisition and reduction procedures will be published elsewhere.

The resulting magnitudes and colours from the telescope runs in 1991 November and December are presented in Table 2. The $(B-V)$ and $(U-B)$ colours have been computed from the *uvby* indices by means of the Turner (1990) transformation formulae. The final errors on V, $(B-V)$ and $(U-B)$ calculated by this method are 0.03, 0.01 and 0.01 respectively. These values differ significantly from the unpublished V, $B-V$ and $U-B$ values of Coyne, Wisniewski & Otton (1978), indicating that the star is currently bluer and fainter than when they carried out their observations.

3 DISCUSSION

Comparing the two optical spectra presented in Figs 1 and 2, one can see the development of a classic 'shell-type' emission spectrum frequently seen from Be stars. The shape of the emission line in Fig. 2 arises in the simplest models from a rotating disc or shell of material around the star. Further examination of Fig. 1 reveals that both the blue and red arms of this double profile were already present. Between the two sets of data, the overall emission was redistributed into two approximately equal wings. In addition, this separation into two peaks allowed the central absorption feature arising from the photosphere of the star itself to become a dominant part of the overall profile. The result was the splitting of the red and blue emission components by the central absorption component.

In fact, this decline in the Hα emission may well have been going on for a much longer period of time. Motch et al. (1991) report an equivalent width of approximately 10 Å in 1990 November and 1991 January, compared to measurements over 10 years ago of 15–30 Å (Sanduleak 1979). While the longer term results must be taken with extreme caution in light of the rapid variability reported in some Be stars, the recent history seems to indicate a decline in activity level associated with a gradual dispersal of the circumstellar disc. Further confirmation of this conclusion comes from the fact that our V magnitudes and colours are, respectively, fainter and bluer than previously reported, thereby supporting the idea of a dispersing circumstellar disc.

This idea that this system is currently in a weak or low state is further substantiated if one uses the combined optical and IR photometric data to assess the overall spectral shape and the necessary dereddening to this system. From the *uvby* indices given in Table 2 it is possible to calculate the reddening to this system as $E(B-V)=0.92$ (Crawford 1978). This reddening implies an intrinsic $(B-V)_0$ for the star of -0.31 and $(U-B)_0=-1.12$. These values are consistent with a O9 or B0 star, rather than the classification of B5IIIe for LSI + 61° 235 given by Slettebak (1985). The misclassification of Be stars as cooler objects happens frequently if allowance is not made for the contributions to the colours from the relatively lower temperature disc. Application of this correction for the interstellar extinction to the combined mean optical and IR photometry results in the magnitudes presented in Table 3. This is also shown graphically in Fig. 3 with the Kurucz model stellar spectrum (Kurucz 1979) for a B0-type star – assuming a $T_{\rm eff}=30\,000$ K and log $g=4.0$. This value for the model fit was determined by holding the log g value constant at 4.0,

Table 3. Observed and intrinsic magnitudes of LSI + 61° 235.

Band	Observed Magnitudes	Dereddened Magnitudes	Expected Magnitudes for B0 star
U	11.69	7.24	7.28
B	12.10	8.36	8.36
V	11.49	8.66	8.66
J	9.96	9.17	9.36
H	9.74	9.25	9.47
K	9.59	9.32	9.59

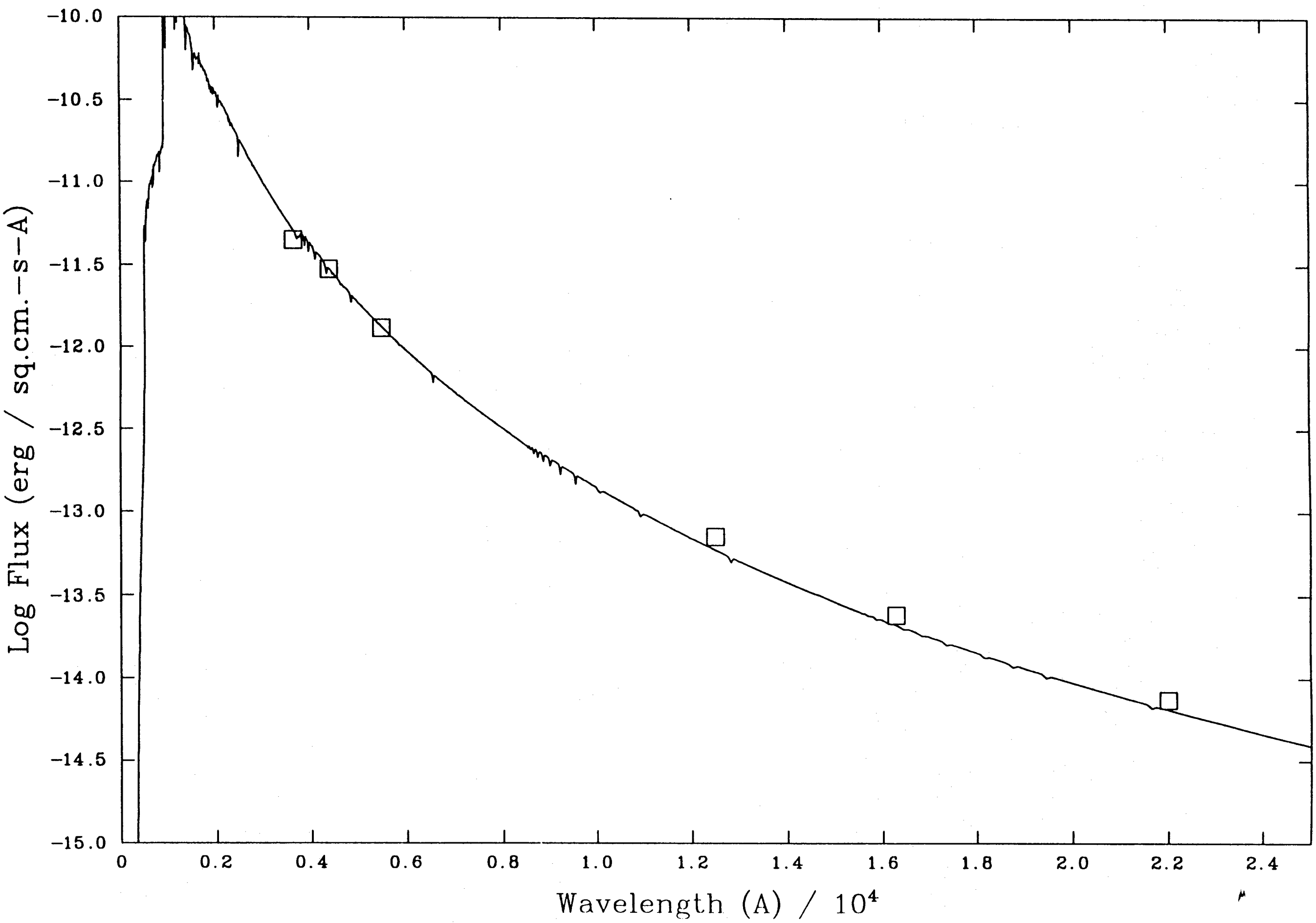

Figure 3. The combined optical and IR photometric data presented in comparison to a typical Kurucz model atmosphere for a B0 star.

varying the temperature and normalizing the fit in the *B*-band (since there should be little or no contribution from any circumstellar disc in this band). This process resulted in a best-fitting temperature of 30 000 ± 5000 K.

From Fig. 3 and Table 3 it is possible to see that the source exhibits a weak IR excess (over the extrapolated stellar emission) arising from free-free emission in a disc or shell structure around the Be star. This kind of behaviour is very common for Be stars and has also been seen in several Be/X-ray systems – see, for example, the results on EXO2030 + 375 (Coe et al. 1988) or V0332 + 53 (Coe et al. 1987). The weak nature of the IR excess is consistent with what one would expect if the circumstellar disc had a very low density and/or was cool to the point of producing negligible emission in the near-IR region. It could, however, still be sufficiently dense to produce weak Hα emission. This is very similar to the results reported by Roche et al. (1992) and Norton et al. (1991) from detailed studies of X Persei carried out during its extended low state. This is further confirmed by locating LSI + 61° 235 on the Hα–IR colour diagram in Fig. 4. In order to produce this diagram, the Hα and $(J-K)$ data have been taken from the Be-star surveys of Dachs & Wamsteker (1982) and Ashok et al. (1984). The $(J-K)$ data were then corrected for interstellar extinction using the observed $(B-V)$ values and the spectral class to determine the intrinsic $(J-K)_0$ colours. The results presented in Fig. 4 clearly show that the source is at the lower end of the possible range of values observed in these systems.

Finally, it is possible to calculate the L_x/L_{opt} ratio for this source using the optical data presented here and the X-ray luminosity and distance from Motch et al. (1991). Use of the best-fitting Kurucz model shown in Fig. 3 integrated over the range 4000–8000 Å, and combination with the source distance of 2.2 kpc, results in an L_x/L_{opt} ratio of 0.03. Though this value is rather lower than the values determined for EXO2030 + 375 (2.8) and V0332 + 53 (1.1) by Coe et al. (1988), it is well within the range of 0.001–10 for high-mass X-ray binaries. In addition, if account is taken of the fact that the *ROSAT* X-ray observations only cover the photon energy range 0.1–2.4 keV, whereas the measurements of the other two systems were over the range 2–10 keV, then the value for L_x would increase by a factor of 2–5 depending upon the exact shape of the X-ray spectrum of this source.

Thus, in conclusion, the system LSI + 61° 235 currently appears to be at a low level of activity, with little material around the Be star. It is possible that, if the system continues to decline even further, it will present us with an opportunity to measure precisely the stellar parameters of the underlying B star. This was successfully achieved for X Persei while it

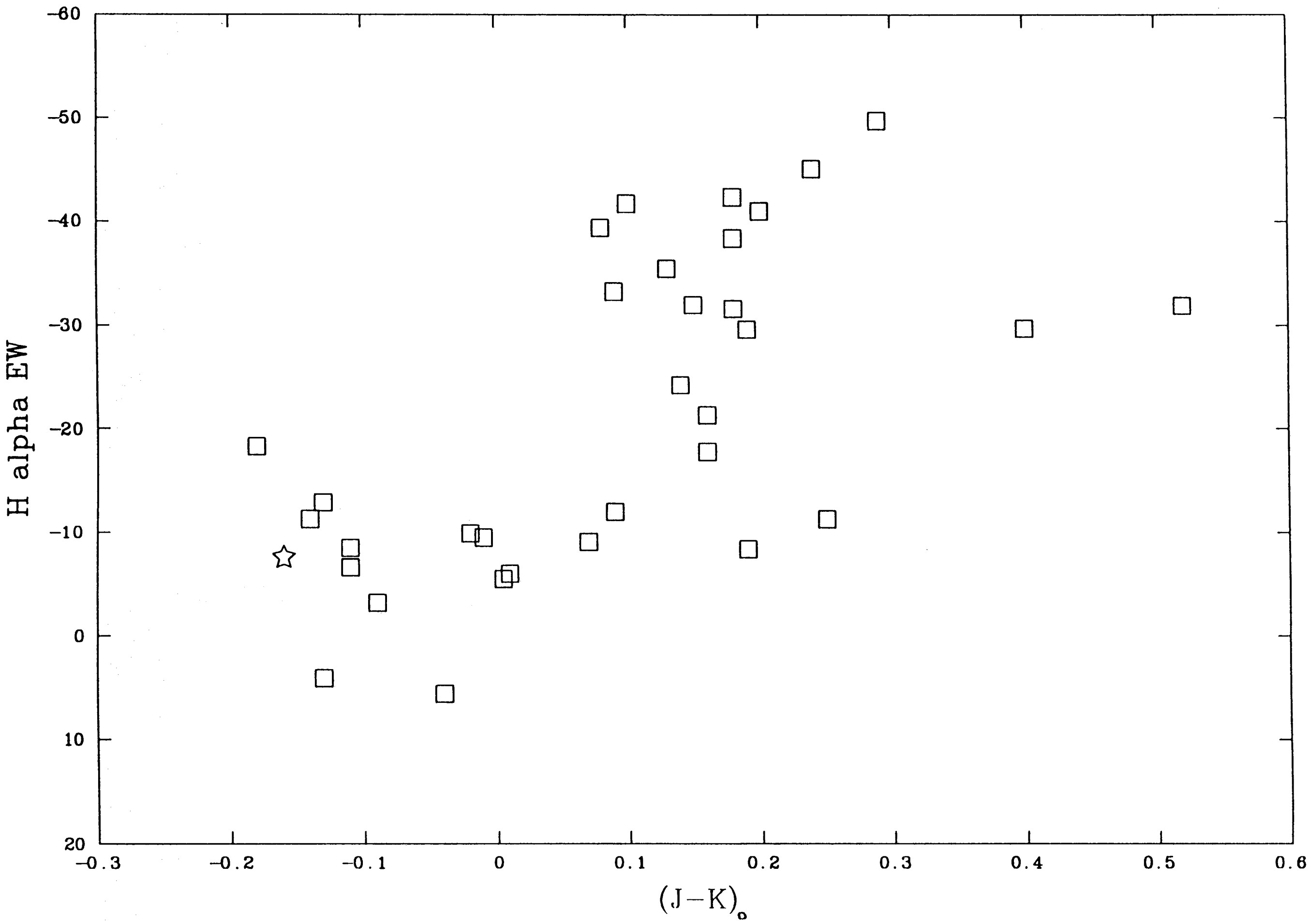

Figure 4. Hα versus intrinsic $(J-K)$ for a sample of 33 Be stars (see text for references). Also shown is the location of LSI + 61° 235 – marked with the star symbol.

was in a similar state (Fabregat et al. 1992), and this kind of information is proving extremely valuable in assessing further behaviour of these complex systems.

ACKNOWLEDGMENTS

The authors acknowledge the support, both software and data analysis facilities, provided by Starlink which is funded by the UK SERC. We are grateful to the Service staff of the INT for providing us with some of the data used here. The TCS is operated on the island of Tenerife by the Instituto de Astrofísica de Canarias in the Spanish Observatorio del Teide. The 1.23-m telescope is operated by the Max Planck Institut für Astronomie in the Spanish-German Astronomical Center in Calar Alto (Almería, Spain). The 1.5-m telescope at Mount Palomar is jointly owned by the California Institute of Technology and the Carnegie Institute of Washington. PR and CE are supported on SERC studentships and SJU acknowledges financial support from Meiko Ltd.

REFERENCES

Ashok N. M., Bhatt H. C., Kulkarni P. V., Joshi S. C., 1984, MNRAS, 211, 471
Coe M. J., Longmore A. J., Payne B. J., Hanson C. G., 1987, MNRAS, 226, 455
Coe M. J., Longmore A. J., Payne B. J., Hanson C. G., 1988, MNRAS, 232, 865
Coe M. J., Everall C., Fabregat J., Gorrod M. J., Norton A. J., Reglero V., Roche P., Unger S. J., 1993, A&A, in press
Coyne G. V., Wisniewski W., Otton L. B., 1978, Vatican Obs. Publs, 1, 257
Crawford D. L., 1978, AJ, 83, 48
Dachs J., Wamsteker W., 1982, A&A, 107, 240
Fabregat J., Reglero V., Coe M. J., Clement R., Gorrod M. J., Norton A. J., Roche, P. D., Suso J., Unger S. J., 1992, A&A, 259, 522
Kurucz R. L., 1979, ApJS, 40, 1
Motch C. et al., 1991, A&A, 246, L24
Nagase F., 1989, PASJ, 41, 1
Norton A. J. et al., 1991, MNRAS, 254, 579
Roche P. et al., 1992, A&A, in press
Sanduleak N., 1979, AJ, 84, 1319
Slettebak A., 1979, Space Sci. Rev., 23, 541
Slettebak A., 1985, ApJS, 59, 769
Slettebak A., 1988, PASP, 100, 770
Snow T. P., Stalio R., 1987, in Kondo Y., ed., Scientific Accomplishments of the *IUE*. Reidel, Dordrecht, p. 183
Taam R. E., Fryxell B. A., Brown D. A., 1988, ApJ, 331, L117
Turner G. T., 1990, PASP, 102, 1331
Waters L. B. F. M., 1986, A&A, 162, 121